

**High-precision VLBI Astrometric Observations of  
Radio-emitting Stars for Detection of Extra-solar Planets**

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*Abstract :* Measurement of the displacement of a radio-emitting star around the barycenter of a possible planetary system can be carried out by astrometric Very Long Baseline Interferometry (VLBI) observations. We have observed the radio-emitting star  $\sigma^2$ CrB at 8 epochs over 5 years by VLBI and fitted its 5 astrometric parameters to the measured coordinates. The post-fit coordinate residuals have an rms scatter of 0.2 milliarcseconds and show no systematic behaviour. We use this result to set a limit on the presence of planets around  $\sigma^2$ CrB and conclude that our present VLBI astrometric precision corresponds to the threshold to detect a Jupiter-like planet around this star. We discuss also the astrometric monitoring program of 11 radio-emitting stars that we are conducting for the Hipparcos space mission and its possible contribution to a long-term planet search program.

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## 1 ) Introduction

Astrometric monitoring of the minute displacement of a star around the barycenter of the system that includes possible planetary companions has been an indirect method for detection of planets for several decades at optical wavelength (van de Kamp and Lippincott 1951). The motion of a single planet in a circular orbit around a star causes the star to undergo a reflexive circular motion around the star-planet barycenter. When projected on the sky, the orbit of the star appears as an ellipse with angular semimajor axis  $O$  given by :

$$O = \frac{m_p}{M_*} \frac{a}{d} \quad (1)$$

where  $O$  is in arcsec when the semimajor axis  $a$  is in AU, the mass of the planet ( $m_p$ ) and the mass of the star ( $M_*$ ) are in solar masses and the distance is in pc. For example, observing the solar system from a distance of 10 pc, the presence of Jupiter would be revealed as a periodic, circular displacement in the Sun's position, with an amplitude  $O$  of 0.5 milliarcsecond (mas) and a period of 11.9 years,

Optical astrometry is generally limited to a precision of a few tens of milliarcseconds (mas) but the best measurements are at the 1 mas level now (Gatewood et al 1992). Technical advances in Very Long Baseline Interferometry (VLBI) with the Mark III recording system (Rogers et al 1983) have provided sufficient sensitivity to detect reliably radio-emitting stars over the last few years. We have carried out VLBI measurements of the position of the radio star  $\sigma^2$ CrB since 1987 and demonstrated that the level of precision is 0.2 mas during 5 years. This level of precision is not SNR-limited and could reach 20 microarcsecond if all systematics could be removed by an improved strategy of observations or data analysis. Such a high level of astrometric precision makes the VLBI technique a new tool for planetary searches.

## 2) Radio-emitting stars

There are about 400 stars that exhibit radio emission as compiled by Wendker (1987). About half of these stars exhibit thermal free-free emission from very large ionized circumstellar envelopes that are fully resolved by VLBI observations. The other stars exhibit non-thermal radio emission (gyrosynchrotron, synchrotron,

coherent emission mechanisms) with typical source size of a few mas or less that match the VLBI angular resolution. These non-thermal radio-emitting stars belong to a wide variety of physical classes, e.g. X-ray, RS CVn, Algol, dMc, FK Com,  $\gamma$  Tauri. Many of these stars can be detected by the sensitive Very Large Array (VLA) in New Mexico, but are too weak to be detected by VLBI. Their radio flux density is only a few tens mJy or less, i.e. 100-1000 times weaker than compact extragalactic radio sources usually observed by VLBI. Nonetheless, 30 stars can be detected by phase-referenced VLBI observations and this number should grow with future improvements of the technique.

We have selected 11 radio-emitting stars with non-thermal emission (7 RS CVn, 2 X-ray and 2 FK Com) for a high-accuracy VLBI astrometric monitoring program. The initial motivation of this program was to measure their radio positions and proper motions to make the future Hipparcos optical reference frame coincidental and at rest with respect to an extragalactic quasi-inertial reference system (Lestrade et al 1992). This is still our main motivation but the results and future developments of our on-going program could contribute to the search for extra-solar planets. One of the selection criteria used to draw up the list of stars in our program was that they be of magnitude lower than 11th to match Hipparcos capability. In the future, this program could expand to monitor a larger sample of stars, especially with the use of the new Very Long Baseline Array (VLBA), which is the antenna array dedicated to VLBI and built by the National Radio Astronomy observatory.

### 3) Phase referenced VLBI technique for high-precision astrometry of weak radio objects

VLBI is an astronomical technique using an array of antennas (two or more) separated by baselines of a few thousands of kilometers which simultaneously observed the same radio source to record its continuum signal over a limited bandwidth, typically a few tens of MHz, on video magnetic tapes. After the observations, the tapes are shipped and the recorded signals of each pair of antennas are cross-correlated on a specialized processor. The observations are usually carried out at centimeter wavelengths (1 to 10 GHz) although recent observations at millimeter wavelength have been successful. The coherence of the radio signals recorded by antennas separated by long distance, and not electrically connected, is possible by locking the

heterodyne reference frequency of the receiver at each site to a frequency standard such as an Hydrogen Maser that has a stability ( $\sim 10^{-14}$  s/s) that allows coherent cross-correlation over 10-15 minutes. Consequently, the observed radio source must have a flux density high enough to be detected over a similar integration time. This is the reason why VLBI is less sensitive than the VLA which is a connected interferometer and one can integrate data for several hours if high sensitivity is required. Of course, VLBI has a much finer angular resolution than the VLA reaching  $< 1$  mas on intercontinental baseline at centimeter wavelengths. At the VLBI processor, the cross-correlation of the recorded signals leads to the measurement of the amplitude and phase of the complex visibility induced by the source brightness distribution convolved with the beam of the antenna pair for the duration of each scan (a few minute integration period).

As mentioned above, the coherence time in standard VLBI is severely limited to less than  $\sim 15$  minutes by non-linear instabilities in the independent frequency standards at the VLBI stations. When a radio source is so weak that it cannot be detected within this duration, one has to resort to the phase-referencing VLBI technique which allows multiple scans to be combined in a single coherent integration period. A reference for the VLBI phase must be established by observing an angularly nearby strong extragalactic source alternately with the weak program source with a cycle time of a few minutes. Such a phase-referencing technique in VLBI allows increased sensitivity through use of much longer integration times (several hours) with minimum coherence loss. This strategy also allows high-accuracy differential astrometry because the prime observable used is the VLBI phase. Since the VLBI interferometer produces milliarcsecond fringe spacings on the sky, the phase of the complex visibility derived from cross-correlation can be used to measure the position of the radio source with an uncertainty corresponding to a small fraction of this fringe spacing. The phase-referencing VLBI technique as applied in our VLBI astrometric program is described in detail in Lestrade *et al* (1990).

#### 4) Results of a series of VLBI observations of the star $\sigma^2$ CrB :

$\sigma^2$ CrB is an RS CVn close binary whose orbital motion has a period of 1.1 day and a semimajor axis of 0.3 mas. Phase-referenced VLBI observations of  $\sigma^2$ CrB were conducted at 8 epochs between May 1987 and August 1992. Observation

dates, flux densities and orbital phases are in Table 1. At 5 GHz, our program used the VLBI array made of the following antennas: the Phased-VLA (NRAO, NM), Bonn (M<sup>1</sup>), Germany), Medicina (Bologna, Italy), Greenbank (NRAO, WVa), Haystack (MIT, Mass), OVRO (Caltech, CA) and, at 8.4 GHz, the VLBI array was made of Goldstone (DSN, CA), Hat Creek (Berkeley, CA), VLA (NRAO, NM), OVRO (Caltech, CA), Haystack (MIT, Mass) and newly commissioned VLBA radiotelescopes (USA). The total data integration times were between 5 and 8 hours at each epoch. The VLBI data acquisition system was the Mark III system used in a mode to record a bandwidth of 28 MHz (Rogers et al. 1983). The corresponding detection threshold is about 2 mJy (100). All the cross-correlation of the recorded signals was carried out at the Mark III Processor at Haystack Observatory (MIT, Mass).

Obser. Date	Orbital phase (Cycle)	Frequency (GHz)	Flux density ( mJy )
87/05/26 04 UT	0.56	5.0	10
88/11/16 17 UT	0.93	5.0	28
89/04/1 306 UT	0.25	5.0	7
90/11/16 23 UT	0.37	5.0	3.8
91/04/12 10 UT	0.86	8.4	19.5
92/01/15 13 UT	0.88	8.4	4.6
92/06/08 04 UT	0.89	5.0	13
92/08/03 05 UT	0.06	8.4	8.3

Table 1 : VLBI observations of  $\sigma^2$ CrB at 8 epochs.

The 5 astrometric parameters of  $\sigma^2$ CrB (2 coordinates, 2 proper motion components and parallax) were estimated by a least square fit with the 16 coordinates measured at the 8 epochs. Figure 1 shows the results of the fit. The uncertainties of the measured VLBI coordinates were set to 0.20 milli-arcsec to make the reduced- $\chi^2$  close to unity for the number of degree of freedom 11 in the fit. The rms of the post-fit coordinates residuals is 0.2 mas. With such an adjustment, the formal uncertainties for the 5 fitted parameters are 0.08 mas for the relative position between  $\sigma^2$ CrB and the reference source 1611-1 343, 0.04 mas/year for the proper motion

and 0.08 mas for the trigonometric parallax. The correlation matrix indicates that the 5 parameters are well separated.

Result of weighted fit for SIGCRB  
 RIGHT ASCENSION (J2000) = 16h14m 41.067491s  $\pm$  0.000005s ( $\pm$  0.00008")  
 DECLINATION (J2000) = 33d 51' 31.87405"  $\pm$  0.00008"  
 P.M. RA (J2000) = - 0.021 427  $\pm$  0.000003s/y ( -0.32141  $\pm$  0.00004"/y)  
 P.M. DEC (J2000) = - 0.08670  $\pm$  0.00004"/y  
 PARALL AXE = 0.04404  $\pm$  0.00008"  
 Epoch for RA and DEC = 90/ 1/ 1 0h UT (2447892 .50JD)

Correlation between parameters:  

Param.:	R-AS	DECL	PMRA	PMDE	PRLX
R-AS	1.00	0.04	-0.40	-0.02	-0.18
DECL	0.04	1.00	-0.04	-0.39	-0.23
PMRA	-0.40	-0.04	1.00	0.02	0.17
PMDE	-0.02	-0.39	0.02	1.00	0.11
PRLX	-0.18	-0.23	0.17	0.11	1.00

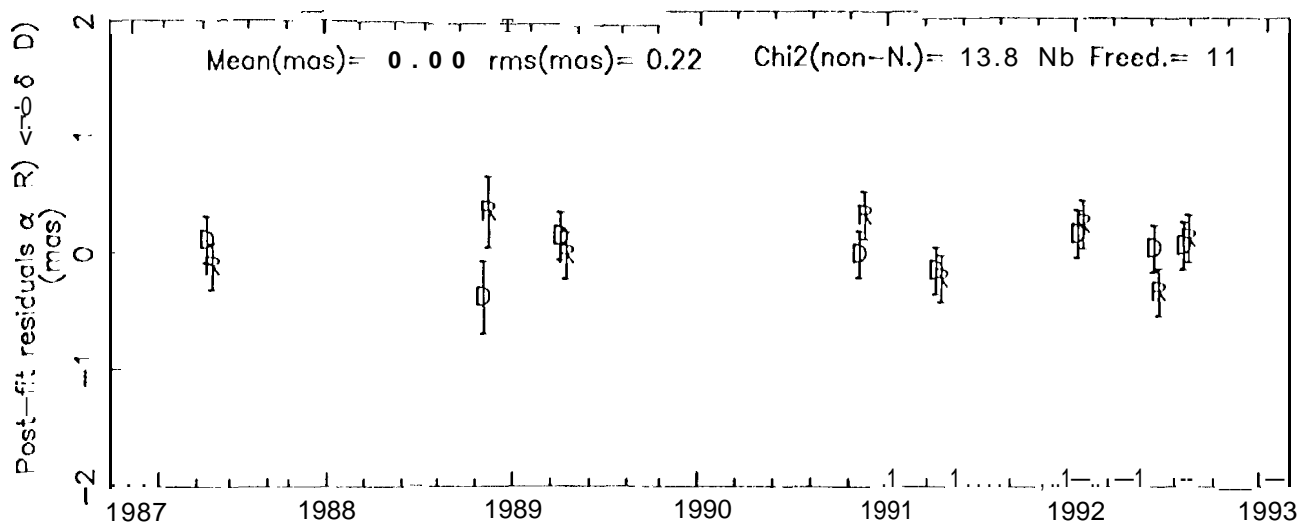


Figure 1: Result of the fit of the 5 astrometric parameters of 02 CrB adjusted to the coordinates measured by VLBI at 8 epochs.

The number of degree of freedom (11) is high enough to make the statistical significance of the formal uncertainties reliable. Various tests have been made for the robustness of the solution. One test has been to make two astrometric solutions, one with the first 4 epochs and one with the last 4 epochs of observations. The table below indicates the parameter differences between the two solutions.

Parameter	Differences
$\alpha$	0.22 mas ( $1.2\sigma$ )
$\delta$	0.19 mas ( $1\sigma$ )
$\mu_\alpha$	0.22 mas/y ( $0.80$ )
$\mu_\delta$	0.24 mas/y ( $0.9\sigma$ )
$\pi$	0.12 mas ( $0.5\sigma$ )

Also, the 5 asymmetric parameters of  $\sigma^2\text{CrB}$  determined by VLBI (see inset of Figure 1) all match, within uncertainties, the best but less precise optical determination by Requi  ne and Mazurier (1987) (for the position and proper motion) and by Jenkins (1952) (for the parallax).

### 5) Implications for the presence of planets around the radio star $\sigma^2\text{CrB}$

The lack of obvious sinusoidal signature in the post-fit coordinates residuals of Figure 1 sets a limit on the presence of planets around  $\sigma^2\text{CrB}$ . The rms of these post-fit residuals (0.2 mas) is an upper limit on systematic departure from linear motion for the star. Eq (1) can be used to exclude a range of planetary perturbations by taking  $\sigma = 0.2$  mas,  $M_\star = 2.26 M_\odot$  and  $d = 22.7$  pc for  $\sigma^2\text{CrB}$ . The *log-log* representation of eq (1) with these parameters is in Figure 2. The diagonal line of constant astrometric signature follows eq (1) and all points above this line represents larger planetary perturbations. We assume that a full orbital period of the planet must be sampled during the total span of observations to separate the sinusoidal planetary signature from the fitted linear proper motion. In these conditions, the maximum semimajor axis  $a$  of a planet corresponds to the total observation span through the third Kepler law. This upper limit on  $a$  is 3.8 AU for our 5 years of observations and is the vertical dashed line in Figure 2. The shaded area indicates the parameter space ( $a, m_p$ ) that are excluded by our observations for a possible planet. Note that for  $a = 3.8$  AU, the mass  $m_p$  is  $0.0014 M_\odot$ . Finally, on Figure 2, we have also shown where a Jupiter-like planet would fall. Interestingly, the present accuracy of our VLBI measurement corresponds exactly to the detection threshold for a Jupiter-like planet around  $\sigma^2\text{CrB}$  when 12 years of data are collected.

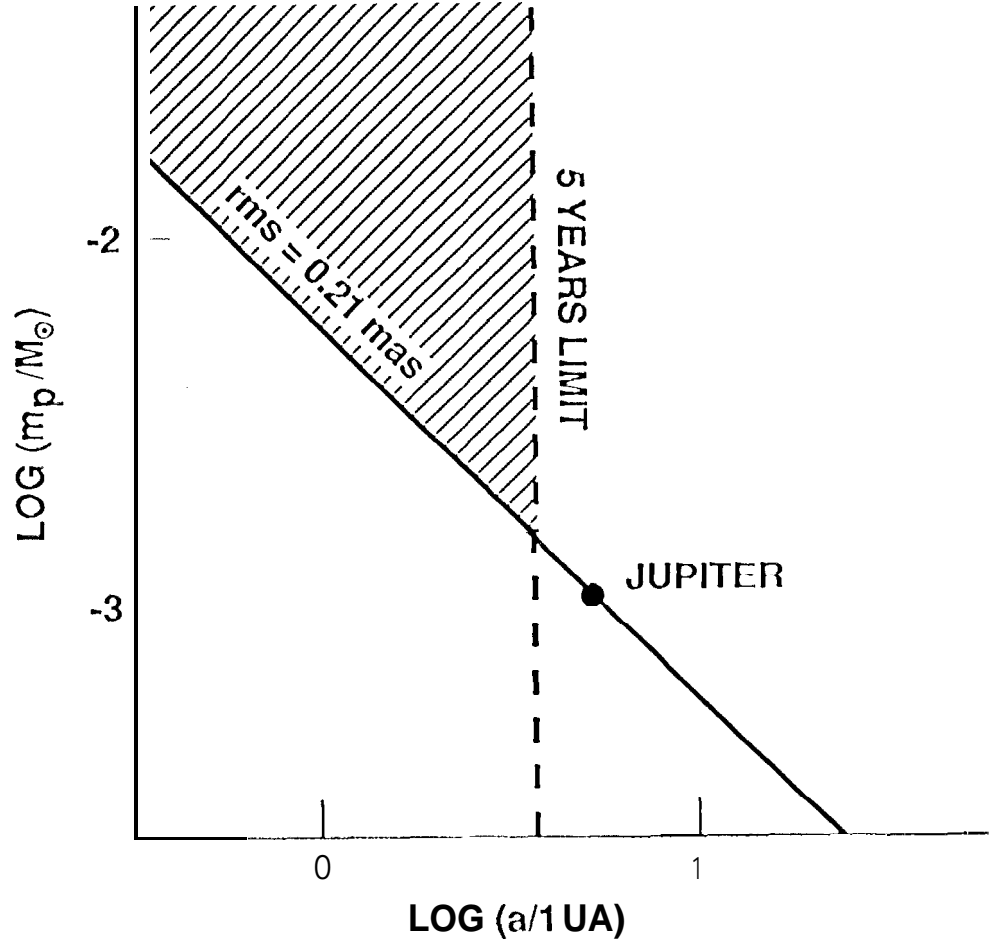


Figure 2: Log-log representation of eq (1) for the rms of the post-fit coordinate residuals of  $\sigma^2 \text{CrB}$ . The shaded area is the parameter space (semimajoraxis  $a$ , mass  $m_p$ ) that are excluded by our observations for a planet around this star.

This interpretation is optimistic since Black and Scargle (1982) note that the the fitted linear proper motion absorbs part of the planetary perturbation. These authors show that with observations sampling a single orbital period, the amplitude of the planetary perturbation is underestimated by as much as 47%. However, if the classical model (position, proper motion and trigonometric parallaxe) is complemented by a sinusoidal function and the *a priori* values for the amplitude, period



and phase chosen to cover a large volume of the parameter space, no absorption of the planetary perturbation would occur and the 3 additional parameters can be fitted.

$\sigma$  CrB is a triple system consisting of a visual pair with a G1 V star ( $\sigma^1$  CrB) separated by 140 AU ( $P=1\,000$  years) from a spectroscopic binary ( $\sigma^2$  CrB = F6V/F8V) whose separation is  $6 R_\odot$  ( $P=1.3$  day). The two orbital planes are co-planar (Barden 1985). The radio emission is identified with the spectroscopic binary classified as an RS CVn with two chromospherically active stars. The masses of these two stars, F6V and F8V, are 1.12 and 1.14  $M_\odot$  (Barden 1985), respectively, and their sum, 2.26  $M_\odot$ , has been used in the analysis above.

The location of the radio centroid within the spectroscopic binary is a crucial question. If the radio emission is associated with only one of the stars, then a total displacement of 0.6 mas correlated with the orbital phase of the system would be seen in our coordinates residuals since the observations were taken at various orbital phase of the spectroscopic system (see Table 1). A precise ephemeris of orbital phase has been established for  $\sigma^2$  CrB by Bakos (1984). The post-fit residuals might be dominated by this orbital motion and we are investigating this possibility with additional observation to cover uniformly the whole orbit. The stability of this radio centroid over time is an important question for a planetary search. There is no detailed model of the radio emitting region that can be used to derive this stability. It must be determined observationally and the rms of our post-fit coordinate residuals (0.2 mas or  $1 R_\odot$  at  $\sigma^2$  CrB) can also be interpreted as a measure of this stability.

Finally, another important theoretical question is to assess the possibility of the formation of a dynamically stable planetary system in a triple stellar system like  $\sigma$  CrB.

### 6) Final remarks

We have demonstrated that phase-locked VLBI observation of the radio star  $\sigma^2$  CrB can achieve an astrometric precision of 0.2 mas. Interestingly, this precision corresponds to the level of perturbation around the linear proper motion of the star expected for a Jupiter-like planet. At present, there are about 30 radio stars that could be monitored for a planetary search program by astrometric VLBI observations. But the scarcity of VLBI observing time has made such a program

unpractical till now. However, the new VLBA should make it possible in the near future. In addition, foreseen technical improvements to enhance the sensitivity of the recording system by the end of the decade should lengthen the list to about 60 candidate stars.

The theoretical precision for an interferometer is  $\sigma_{\alpha,\delta} = \frac{1}{2\pi} \frac{1}{SNR} \frac{\lambda}{B}$  (Thompson, Moran, Swenson 1986) and for our observations,  $\sigma_{\alpha,\delta}$  is 20 microarcseconds with  $B \approx 3000$  km,  $\lambda = 6$  or 3.6 cm and  $SNR > 15$ . Hence, the astrometric precision achieved for  $\sigma^2$  CrB is not SNR-limited (Signal-to-Noise-Ratio-limited). There are at least three systematic error sources that prevent reaching this ultimate precision of the observations: 1) the extrapolation of the reference source VLBI phase in switched observations to the time of the star observation, 2) the differential contribution of the atmosphere and ionosphere along the two lines of sight to the reference source and target star and 3) the structures of the reference source and, possibly, of the star. The atmosphere and ionosphere propagation effects could be modelled by improved calibration and the structure of the reference source mapped with the data themselves. But the main error source, for the moment, is the extrapolation of the reference source VLBI phase over 2 to 3 minutes because of the switched observations. This can be eliminated entirely if the reference source and the star are angularly close enough to be in the main beam of the antennas but this is a rare situation. A more general approach would be to use VLBI baselines with two antennas at each end for pointing continuously at the reference source and the star. The two antennas at each site should be phase locked to the same frequency standard (Hydrogen maser). The antenna pointing at the relatively strong reference source could be smaller. This prospect is not presently considered for the VLBA.

Table 2 summarises the relevant information for the 11 radio-emitting stars of our Hipparcos astrometric program in order to compute the total sky displacement  $2 \times \theta$  from eq 1 expected for a Jupiter-like planet around these stars. The values calculated for  $2 \times \theta$  in this table compare favorably to the potential SNR-limited astrometric precision of phase-referenced VLBI observations on intercontinental baselines. The last 2 stars in Table 2 (Hubble 4 and HD 283572 of the Taurus-Auriga dark clouds) are Pre-Main-Sequence stars that are not part of our current program but have been detected on intercontinental VLBI baselines by Phillips, Lonsdale and Feigelson, 1991. These two stars were part of a survey at 1.3 millimeter and were not detected while other stars of the cloud were detected. The detections

were interpreted as evidence for a dust-disk around the stars, i.e. proto-planetary material (Beckwith et al 1990). One can speculate that Hubble 4 and HD 283572 are more evolved and, possibly, that their initial dust-disks have already collapsed into planets.

Star	Class	Distance (pc)	Masses hot/cool ( $M_{sol}$ )	Spectral Type	$2 \times \theta_{Jupiter}$ ( $\mu$ as)
LSI 61 303	X-ray	2000			
Algol	Algol	27	3.6/0.79	K0IV/B8V	80
UXARI	RS CVn	50	> 0.63/ > 0.71	G5V/K0IV	<160
IR 1099	RS CVn	36	1.1/1.4	G5IV/K1IV	100
111) 1'2834471 MS (WTT)		160	1.74	K3	35
IR 5110	RS CVn	53	1.5/0.8	F2V/G0IV	80
$\sigma^2$ CrB	RS CVn	21	1.12/1.14	F6V/G0V	210
Cyg X 1	X-ray	2000			
111) 199178 FK Com		140-90	3.2 ?	G5 III-IV	> 25
AR Lac	RS CVn	47	> 1.3/ > 1.3	G2IV/K0IV	80
IM Peg	RS CVn	50	4 ?	K2 III-IV	25
Hubble 4	PMS (WTT)	160	0.5 - 2.0	K7	> 30
HD 283572	PMS (WTT)	160	0.5 - 2.0	G5	> 30

Table 2 : The 11 radio-emitting stars of our VLBI program and the relevant information to compute the total sky displacement  $2 \times \theta$  for a Jupiter-like planet around them.

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